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Application of a Generalised Engineering Methodology for Thermal Analysis of Structural Members in Fire

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ABSTRACT

The GeniSTELA code has been developed as a generalised CFD-based approach for thermal analysis of protected steelwork in fire. This is a quasi-3D approach with computation of a "steel temperature field" parameter in each computational cell. The methodology accommodates both uncertainties in the input parameters and possible variants to the specification by means of simultaneous calculations. A framework for the inclusion of temperature/time-dependent thermal properties, including the effects of moisture and intumescence, has been established. GeniSTELA has been implemented as a submodel within the SOFIE RANS CFD code. This paper presents the full-scale application of the method for two full-scale scenarios: standard tests in fire resistance furnaces and the post-flashover BRE large compartment fire test. Comparison with test results permits model validation whilst model capabilities are demonstrated by simultaneous calculations for consideration of a range of parameters of interest, including member size and protection material properties. The computational requirements are also addressed, with the efficient use of the method being assessed considering aspects such as number of parametric variants and the frequency of GeniSTELA call compared to flowfield solution, i.e. the balance between fluid and solid-phase analyses. The results enable identification of the critical parameters which affect the thermal performance. Ultimately, the steel temperature field prediction provided by GeniSTELA provides far more flexibility in assessing the thermal response of structures to fire than has been available hitherto, demonstrating the potential practical use of the method.

1 INTRODUCTION

A novel methodology for generalised thermal analysis of structural members in fire, known as GeniSTELA (Generalised Solid ThErmaL Analysis), has been developed and verified, as described previously [1-3]. The model is developed as a quasi-3D model, which is an essentially 1D heat transfer model with 2D and 3D effects corrections, implemented in a CFD environment with computation of a "steel temperature field" parameter in each computational cell. The reduction of the model from full 3D to quasi-3D allows variation of both uncertainties in the input parameters and possible variants to the specification by means of simultaneous calculations. A framework for the inclusion of temperature/time-dependent thermal properties, including the effects of moisture and intumescence, has also been established [2,3]. GeniSTELA has been implemented as a submodel within the SOFIE RANS

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CFD code. Full details of the conceptual model have been described previously, together with example results for hypothetical parameter variations [1-3]. For the latter, representative empirical values are adopted for the initial conditions, the dry thermal properties, moisture content, etc., and their influence is studied by exercising the model with different sets of input parameter values.

Two full-scale application examples are now provided to further demonstrate the practical use of the method. The first is a standard fire resistance test apparatus, based on the Warrington $9m^3$ wall furnace, and the second is the post-flashover BRE large compartment fire test. A furnace test is chosen in order to decouple uncertainties in temperature prediction from the thermal response problem whilst at the same time assessing the latter in the context of results available from testing. For this to work, it is clearly essential that the basic CFD model must reproduce the standard temperature-time curve, as a minimum, and to achieve this could be quite challenging, not least because no detailed information is normally available on the gas flow rates in furnace testing. Nevertheless, it is possible to achieve a match at least at the level of the overall furnace temperatures by iteratively adjusting the gas flow rates, as has been reported previously [4]. The results of the furnace simulation are used to verify the model for thermal response of protected components, referencing expected performance based on fire resistance ratings. The compartment fire test also permits assessment of the predictive capabilities for the steel temperature field, but for the more general case of natural fire exposures. Again, it is a challenge to first reproduce the measured thermal fields, though in this case the fuel supply rates can be determined at least approximately by reference to crib mass loss data [5-7]. Another significant uncertainty in natural fire derives from the lack of information on the optical properties of the combustion gases (these were not directly measured) but sensitivities can be considered based on some assumed values [7].

2 TEST SCENARIOS

As aforementioned, two cases, the Warrington full-size fire resistance furnace test and the BRE large compartment fire test, are referred to in this paper. Their experimental details are described below.

2.1 Warrington fire resistance test furnace

2.1.1 Experimental arrangement

Fig. 1 shows a view of the fire resistance test furnace with the front specimen removed. The internal dimensions of specimen and exhaust walls are 3.08m high by 3.06m wide; the width of the furnace, i.e. distance between the specimen wall and the exhaust wall shown at the rear, is 0.93m. There are a total of fourteen burners arranged opposite each other in two sets of seven. Here, the test specimen is taken to be a steel sheet of thickness 50mm; all the other walls are lined with a ceramic material, approximately 150mm in thickness. The default material properties, for ambient conditions, are listed in Table 1 below.

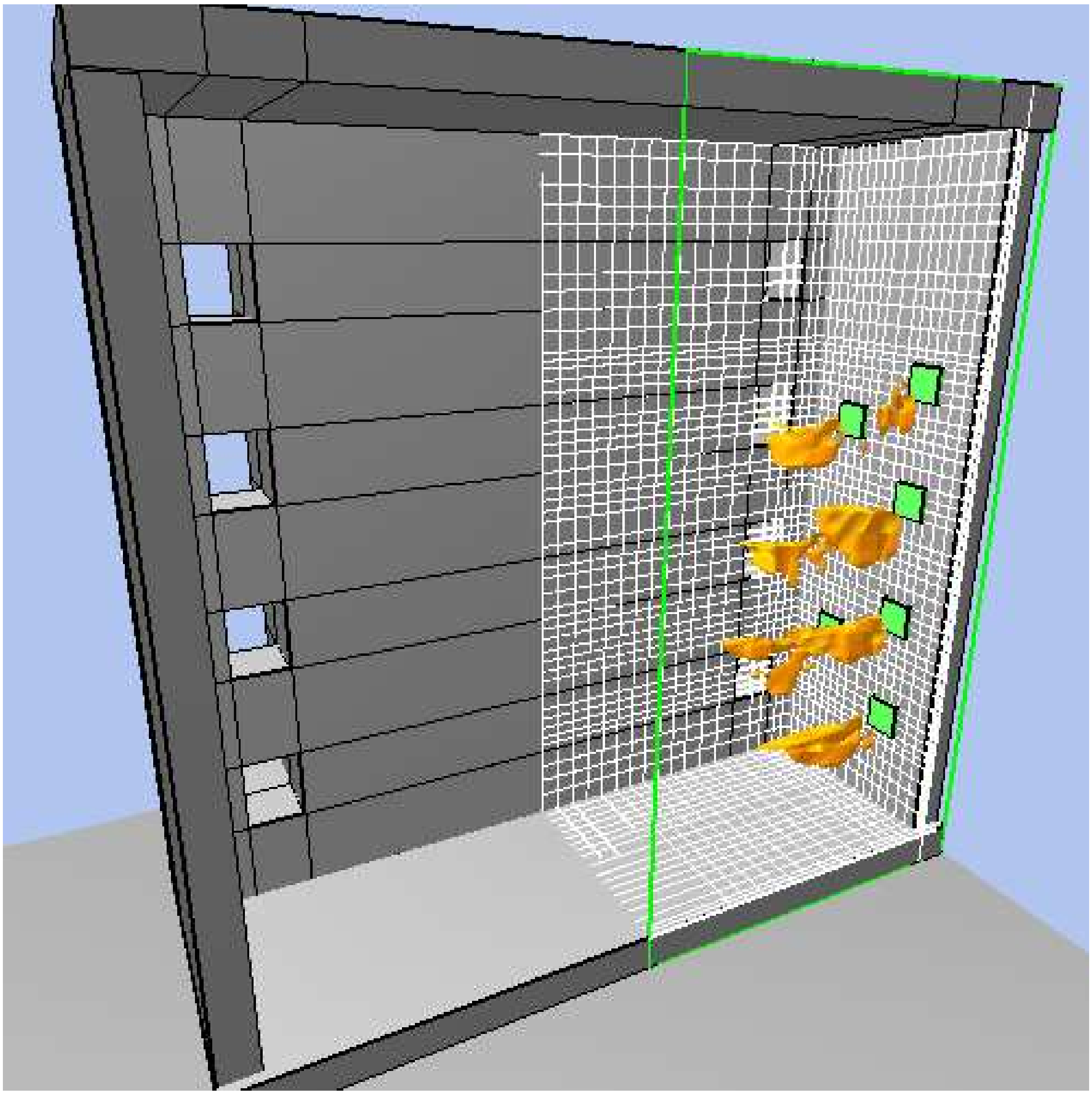

Fig. 1. Illustration of the Warrington wall furnace geometry

	Steel	Ceramic
Thermal conductivity (W m^{-1} K^{-1})	42.0	0.34
Specific heat capacity (J $kg^{-1}K^{-1}$)	530	1000
Density (kg m^{-1})	7850	880
Surface emissivity	0.80	0.90

Table 1. Physical parameter values of steel and ceramic at ambient temperature [4]

This is a gas-fired furnace with natural gas supplied to the centre slot of the burner quarls and sufficient air for a stoichiometric balance via a surrounding duct. In the test, a total of 18 1.5mm thermocouples were used to monitor the gas-phase temperatures. Nine were located 100 mm from the specimen surface, three positioned on the furnace centreline, and three offset 0.7m towards the burners on each side. The vertical positions were 0.52m, 1.43m and 2.34m from the floor. The other nine thermocouples are located near the exposed specimen surface at equivalent locations [4]. The positions of the thermocouples are shown in Fig. 2.

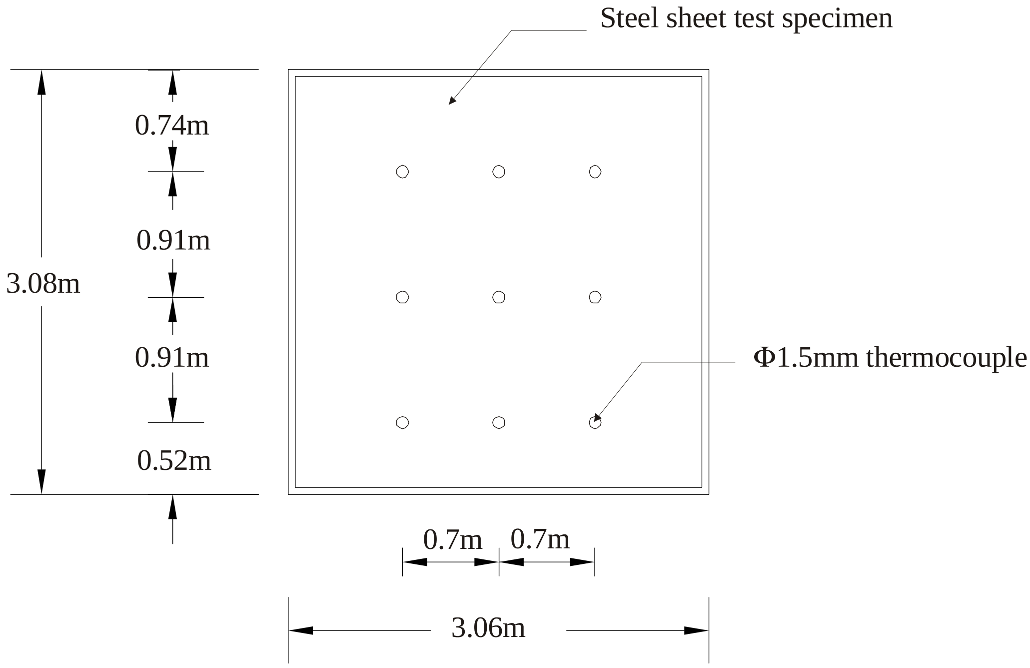

Fig. 2. Position of the thermocouples

2.1.2 Experimental data

Unfortunately, detailed measurements of gas flow rates are not typically recorded in standard fire tests; however, a nominal value of 2160 cu-ft(gas)/hr was available for this furnace providing an initial guideline. In simulations with a steel specimen it was found necessary to boost this by a factor of up to three in order to achieve a match with the standard heating curve, i.e. based on the predicted thermocouple temperatures. Fig. 3 shows the adopted time variation of the overall gas and air flows together with the heat release rate for a single burner.

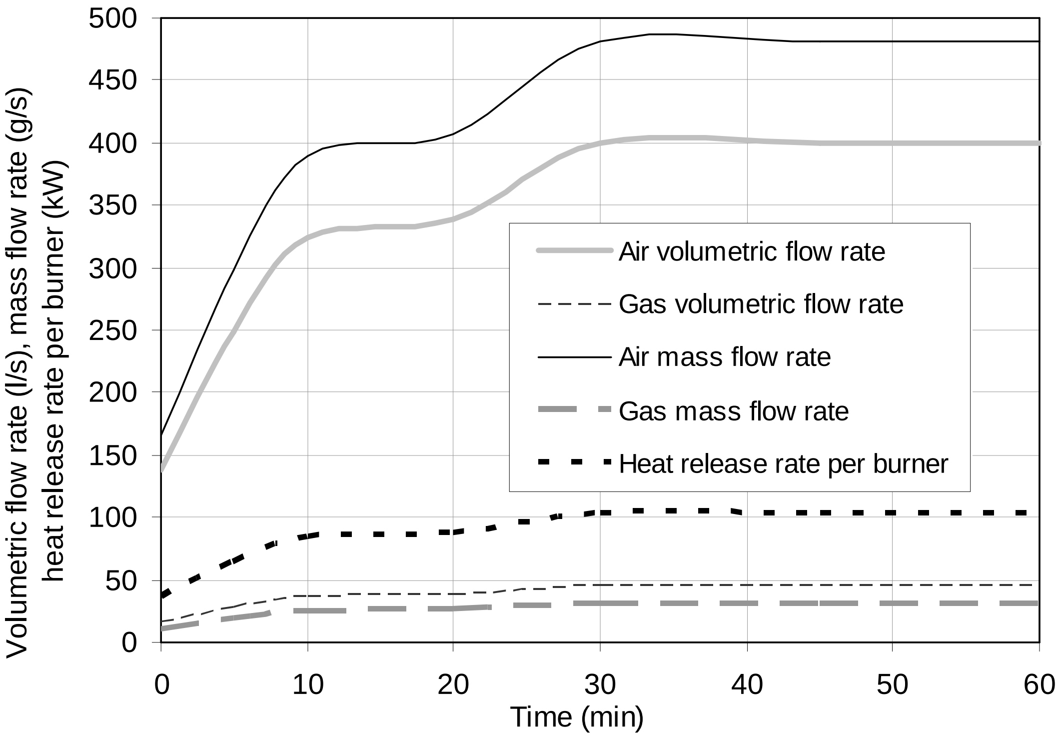

Fig. 3. Time variation of air and gas flow rates, and burner heat release rate

2.2 BRE large compartment

2.2.1 Experimental details

A series of eight full-scale fire tests were undertaken at BRE as part of the European Coal and Steel Community (ECSC) research project, for validation of the Natural Fire Safety Concept (NFSC2). These tests were carried out in a large compartment, nominally 12m x 12m in plan, with a ventilation factor of approximately 0.09 $m^{½}$ and fire loading of 40 kg/m^2 wood or equivalent wood and plastic fuel [5-7]. The test variants looked at the effects of ventilation conditions (by varying opening position and geometry), fire load composition (using different fuels, but maintaining the same calorific value) and thermal insulation of the compartment boundaries (by changing the wall lining materials). The detailed analysis of the experimental measurements has been reported for test 8, and the same test is studied here for GeniSTELA application. The test details from *in situ* measurements at the time of the test are summarised in Table 2 below [6,7].

Parameters	**Descriptions**
Fire load type	Cellulosic and plastic – 80% wood and 20% plastic
Geometry	Internal room geometry 12 m x 12 m plan by 2.95 m high
Ventilation conditions	Opening at the front only: full-height doorway centred on each symmetric half of the compartment Geometry: 3.60m wide x 2.95m high » opening factor $0.084m^{1/2}$
Materials	Light-weight concrete blocks (masonry walls) Precast concrete (ceiling slabs) Steel - 254x254UC73 section (main beams and columns) Sprayed fibre fire protection material (Fendolite MII) applied over underside of ceiling slabs and on beams and columns
Measured parameters	1. Fuel mass loss rate (8 cribs) 2. Gas temperatures 3. Heat fluxes (steel billets measurement devices) 4. Wall temperatures 5. Gas velocities The detailed measurement locations are accessible [6].

Table 2. Summary of BRE large compartment test 8.

The basic nominal/ambient material properties are listed in Table 3 below:

Material	Thickness (m)	Conductivity (W/m/K)	Density (kg/m^3)	Specific heat capacity (J/kg/K)
Light-weight concrete	0.19	0.42	1375	753
Precast concrete	0.15	1.5	2400	1500
Fendolite MII	0.025	0.19	680	970

Table 3. Material properties for BRE large compartment fire test

Figs. 4-6 show the pre-test conditions and fire development for tests 1 and 8 (test 1 used no plastic in the fuel load, but was otherwise the same as test 8).

Fig. 4. Right-hand opening in BRE large compartment prior to test 8

Fig. 5. Right-hand opening showing early fire development in test 8

Fig. 6. Front openings showing later fire development in test 1

2.2.2 Experimental data

A variety of thermal parameters were measured in the test, encompassing temperatures, velocities and heat fluxes in the gas phase, as well as steel temperatures in protected beams, columns and indicatives, with and without protection, in the solid phase [5-7].

3 RESULTS AND ANALYSIS

3.1 Warrington fire resistance test furnace

The standard heating curve was approximated by running simulations based on the gas/air inflow specifications given in Fig. 3, cf. [4]. 30576 cells were used for a symmetric half geometry, using one-second timesteps, eddy breakup combustion, convected scalar soot (1.2% in inflows) and DTRM radiation (2x4 rays, with Truelove CH4+soot coefficients). The characteristic furnace temperature was obtained from the weighted average of the predicted thermocouple temperatures at the nine measurement locations used in the test (see Fig. 2). Thermocouple temperature predictions were obtained from the in-built thermocouple simulation model [4,10], based on a specification of cylindrical 1.5mm diameter wires. The predicted values varied quite markedly around the furnace, cf. Fig. 7, as noted previously [4], and there is a knock-on effect on the steel temperature predictions, which peak in the region of the burners, cf. Fig. 8.

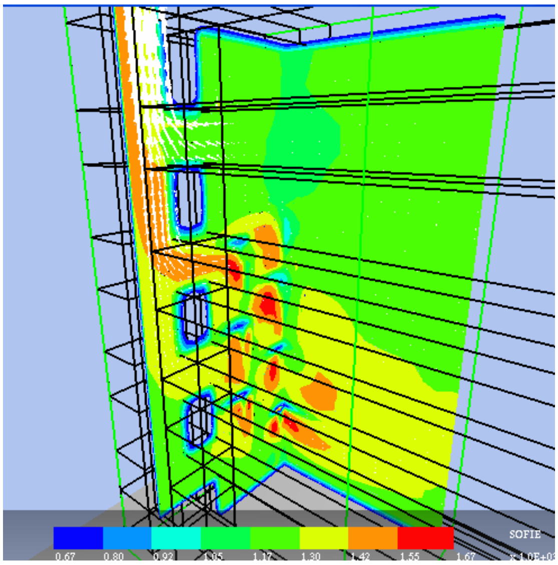

Fig. 7. Predicted gas temperature field at 1 hour

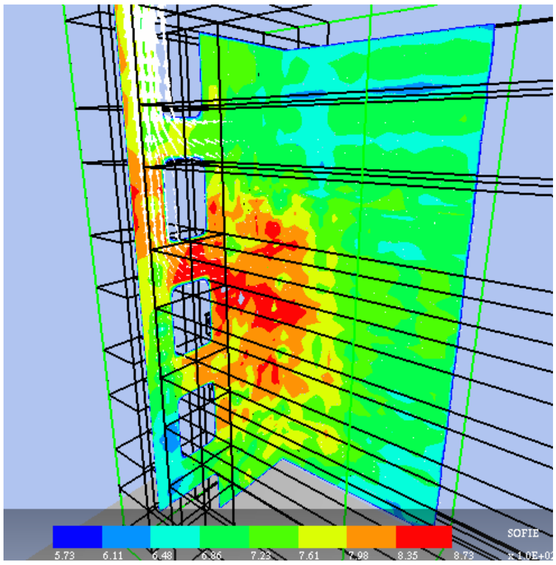

Fig. 8. Predicted steel temperature field at 1 hour

The performance of the GeniSTELA model was analysed by running simultaneous computations for different member specifications, around a default of UC254x254/73 sections, including different types of protection system (sprayed fibre, and intumescent paint, cf. [2]), protection thicknesses and section factors, i.e. flange thicknesses. Transient simulations were performed, with GeniSTELA called on every timestep.

3.1.1 Simulation results

Fig. 9 shows the various temperature profiles, averaged across the locations of the vertical rakes, at a time of one hour. Even at this stage of the test the non-homogenous nature of the thermal fields are clearly apparent, with some locations having predicted temperatures well in excess of the nominal heating curve, and vice versa elsewhere. However, these are seen not to have too much effect on the steel temperature; the latter is still well inside the 550°C contour, consistent with one hour fire rating using this protection system.

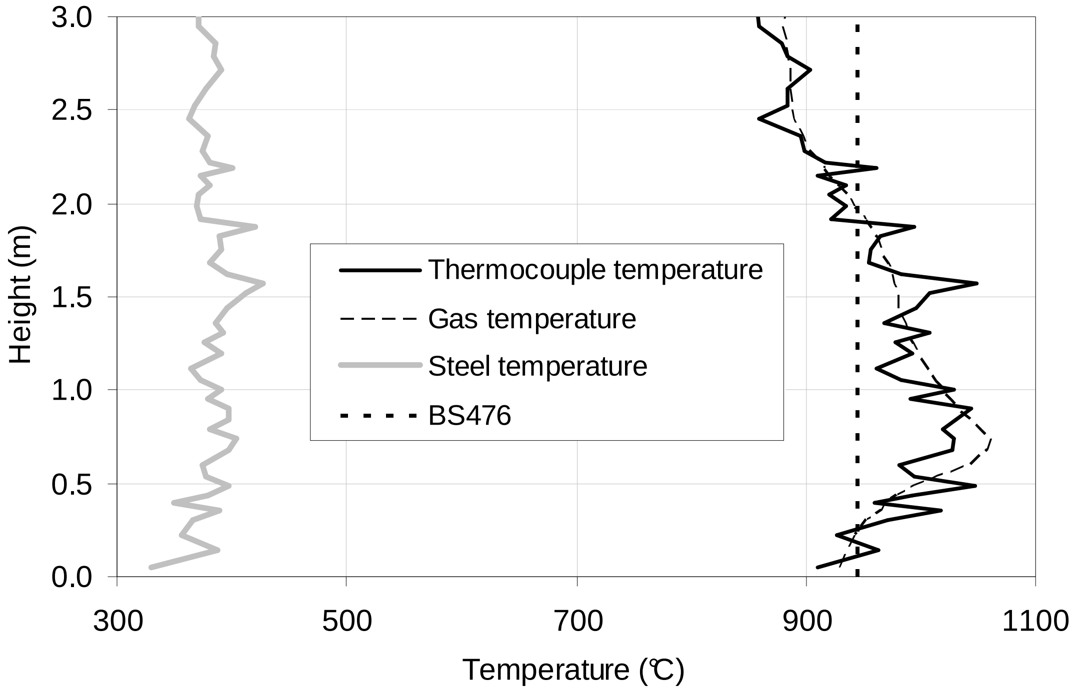

Fig. 9. GeniSTELA predictions of furnace temperature profiles, at 1 hour

3.1.2 Sensitivity study results

Some results from a sensitivity study are shown in Figs. 10 & 11 for the effects of changing the steel flange thickness (spanning UC 254x254/73,107,167) and different types of protection material. As expected, the change of section factor has a big effect on the heating rate. For the latter case, the two materials were chosen to be thermally equivalent, i.e. they provide the same fire resistance rating, with the initial thickness of the intumescent being about 100 times smaller than for the sprayed fibre. The computed steel temperatures are consistent with this expected equivalence.

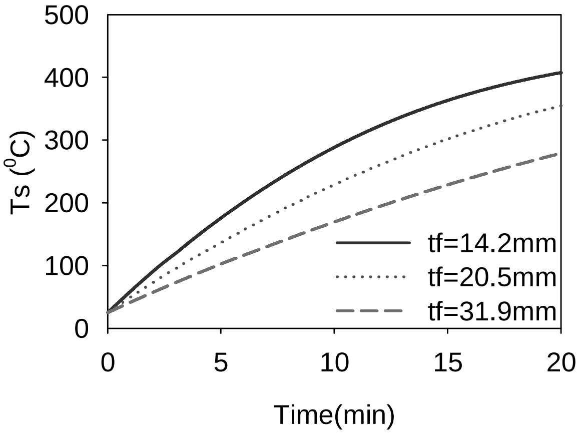

Fig. 10. Effect of flange thickness on steel temperature

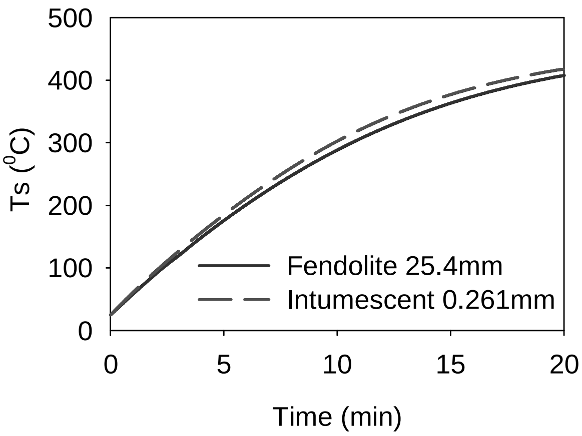

Fig. 11. Effect of protection thicknesses on steel temperature

3.2 BRE large compartment

The thermal response of the protected steel indicative, UC254x254/73, in the BRE large compartment test [7], is examined. The performance of the model was assessed by performing sensitivity studies, looking at the effects of a range of numerical and physical parameters. Comparisons were also made with the results from the EC3 protected member equation [8].

Figs. 12 & 13 provide an illustrative comparison between the experiment and the modelling, for fire test 8.

Fig. 12. Post-flashover fire stage in BRE large compartment test 8

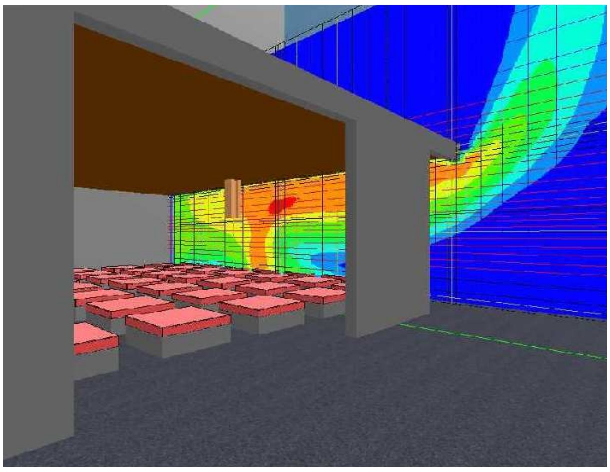

Fig. 13. Predicted temperature field in BRE large compartment test 8

3.2.1 Simulation results

Gas and steel temperatures were computed using SOFIE and the coupled GeniSTELA code. In qualitative terms the results showed the expected differences in steel and gas temperature fields, with relatively higher steel temperatures within the depth of the compartment compared to the openings. This is consistent with the fact that the thermal exposures are more severe deeper into the fire [7] and the model predictions from GeniSTELA are heavily influenced by the radiative terms, $\dot{q}''_r$, derived directly from the CFD calculation.

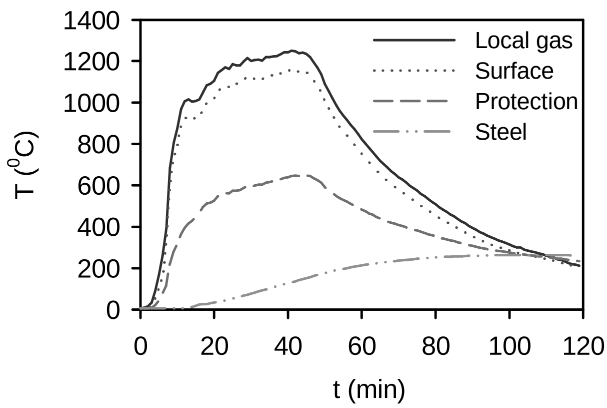

Fig. 14. Temperatures at protected indicative, test 8

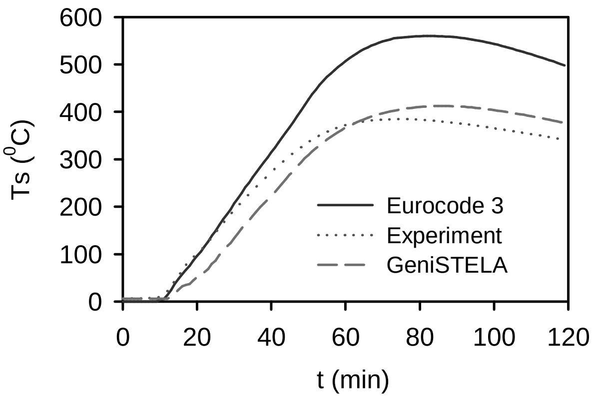

Fig. 15. Comparison of steel temperatures

Fig. 14 shows the temperature predictions for the protected indicative within the compartment. There is a large temperature gradient across the protection. Fig. 15 shows a comparison of the predictions of steel temperature with the test together with EC3 prediction. The latter exceeds the measure temperature reflecting some conservatism in this semi-empirical method, while the prediction from GeniSTELA indicates a sufficient match with the test.

4 COMPUTATIONAL REQUIREMENTS STUDY

The overall computational requirements have been assessed in terms of the CPU time usage. Also, the potential for reducing the frequency of the calls to the GeniSTELA steel temperature solver has been explored by changing this from the default of once every 10 iterations. This default was determined to match the usual frequency of calls to the radiation solver, since one of the key drivers of the thermal response is the radiation field and in most cases there is no benefit in recomputing steel temperatures if this has not been updated. The change in GeniSTELA call frequency is realised by introducing a timestep factor variable (*tfactor*) in the model in order to increase the intervals between calls.

The results showed that GeniSTELA uses around 1% of the CPU time for the flow solver, including radiation, when called at the default interval of 10 iterations. Simulations were then undertaken with a *tfactor* value of 10 for a localised fire scenario, with a constant fire size, having realistic steel temperature increases in 10 minutes. Fig. 16(a) shows the results for the respective steel temperature predictions, confirming that even when called only once per every 100 main solver iterations, i.e. with just six calls of the GeniSTELA solver altogether, there is a very small effect on the final steel temperature result, especially at latter times. Fig. 16(b) shows the evolution of the percentage temperature difference. It is obvious that the discrepancy is only important in the early stage, with the maximum difference being only of order 8%, mostly within 3%. Using an intermediate value of *tfactor*=2 gave results much closer to the default case, with a maximum discrepancy of only 1.5%.

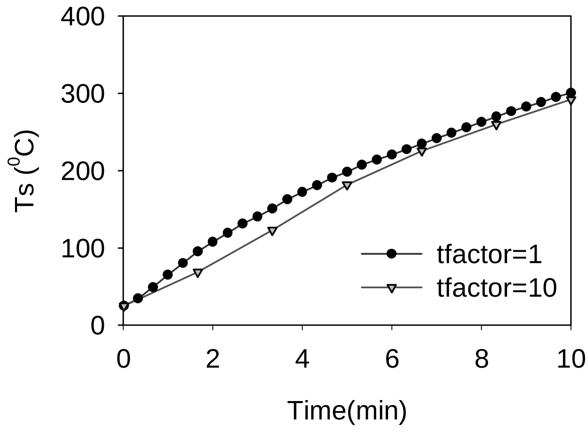

Fig. 16a. Predicted steel temperatures with tfactor=1 and 10

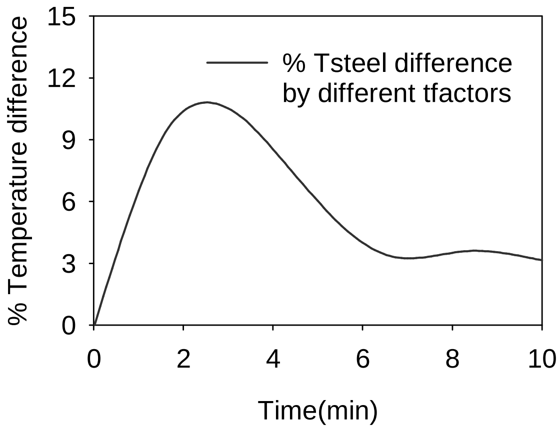

Fig. 16b. Difference in steel temperature against time using tfactor=1 and 10

The above findings are of course only of relevance for this particular steady fire, and for more general cases, where the heat release rate may be changing rapidly, higher frequencies may be required. In practice, the frequency of the GeniSTELA call could be adjusted by automatic selection linked to heating rates, in order to achieve the best efficiency. Nevertheless, this initial study suggests that a full set of parametric calculations (10-100 cases) could be afforded without any significant compromise of accuracy, before the GeniSTELA analysis becomes the dominant part of the computation.

5 CONCLUSIONS

Application of the generalised methodology for thermal analysis of protected steel structures in fire (GeniSTELA) has highlighted a number of issues to do with practical use of the code. The first case study, the fire resistance furnace, is illuminating since it reveals the degree of thermal exposure variation existing within the furnace even well into the test. Of course, furnaces test components as a whole, e.g. beams, columns or assemblies, and it may therefore be problematic to make comparisons between the detailed local predictions of steel thermal response available from GeniSTELA and the global performance of components. This is a similar problem to comparing the results of CFD and zone models, and the resolution may be to take averages or characteristic values, e.g. from locations where the predicted thermal exposures most closely match the average of the standard temperature-time curves, where appropriate. Sensitivity studies reveal the expected dependencies on member specification, and the ability of the model to reproduce the thermal equivalency between different protection systems which provide the same nominal fire ratings has been shown.

For the more general case of the post-flashover fires in a large compartment fire test, reasonable matches were obtained against measured thermal response in a protected steel indicative. Here there are significant uncertainties associated with the temperature-dependent thermal properties of the protection material, and in practice even its application thickness is rather variable; the sensitivity of the results to a number of these uncertainties can easily be investigated in further parametric variants on member specification.

Finally, encouraging results concerning the computational requirements have been demonstrated which suggest that simultaneous computation of larger parametric sets, encompassing 10-100 cases, may well be feasible. Possibilities for further efficiencies in GeniSTELA operation have been identified, in particular, a reduction of the call frequency, which could in principle be automated. When it is possible to assume a quasi-steady fire, much greater efficiencies can be achieved, since the GeniSTELA analysis can be completely decoupled from the CFD simulation, called only as a post-processing operation.

Overall, the results serve to illustrate the importance of using generalised methodologies in tackling fire thermal response problems, providing a possible new approach for performance-based design of protected steel structures.

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